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Investigations on air-fuel mixing and flame characteristics of biodiesel fuels for diesel engine application

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HIGHLIGHTS

- The biodiesel fuels showed poor atomization characteristics than diesel.
- The SMD values of biodiesel fuels were 13% larger than diesel.
- Biodiesel fuels had leaner air-fuel mixture than diesel due to oxygen species.
- Biodiesel fuels showed faster soot oxidation process than diesel fuel.

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ABSTRACT

In this study, the spray and combustion phenomena of biodiesels were investigated in a constant volume combustion chamber (CVCC). Mineral diesel was used as a baseline fuel and biodiesels derived from waste cooking oil, Karanja oil, and Jatropha oil were utilized to investigate the effect of fuel properties on spray and combustion processes. Experiments were performed at high temperature and pressure conditions in order to simulate the atmospheric environment of a diesel engines. Test fuels were injected at an injection pressure of 80 MPa using a common-rail equipped solenoid injector. Macroscopic evaporation characteristics were analyzed by high-speed shadowgraphy technique under evaporating conditions. The representative droplet size distribution and Sauter mean diameter (SMD) were measured using the Phase Doppler Interferometry (PDI) technique, which was applied to study the spray atomization characteristics of the fuels. The air-fuel equivalence ratio in the spray was calculated using mathematical correlations. The quantitative estimations of soot generation in the spray flames were compared using Hue number analysis. From the shadowgraphy images, the biodiesels showed slower air-fuel mixing characteristics than the baseline diesel due to their inferior volatility. While diesel evaporated abruptly after the fuel injection, the biodiesels showed dense liquid regions in the center of the spray plume. Biodiesels also exhibited larger SMD than the baseline mineral diesel in the fuel spray because of their higher density, viscosity, and surface tension. Despite having poor spray atomization characteristics, the calculated equivalence ratio of biodiesels was lower than that of the baseline diesel. This trend was attributed to the oxygen content of biodiesel. The flame luminosity and visible spray flame duration of biodiesels were lower than those of diesel, while the biodiesel spray flames exhibited lower sooting tendency than the baseline diesel.

1. Introduction

Spray and air-fuel mixing processes play a substantial role on engine combustion and emission characteristics in direct injection diesel engines [1,2]. These topics have been received much attention for engine performance improvement [3–5]. Overall mixture formation and combustion process in diesel engines are depicted in Fig. 1 [6]. The air-fuel mixture formation is controlled by in-cylinder air motions (squish flow, swirl, and tumble), injection parameters (injection timing, injection pressure, and injection quantity), fuel properties (density, viscosity, surface tension, and volatility), and fuel injection system characteristics (high pressure pump and injector performance). Turbulent

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Nomenclature

$\varnothing(x)$	equivalence ratio at any axial location x [a.u.]
$\varnothing_{\Omega}$	equivalence ratio [a.u.]
$\left(\frac{A}{F}\right)_{st}$	stoichiometric fuel-air ratio [a.u.]
X	axial location in the spray [mm]
X^*	characteristic length scale [a.u.]
ρ_a	ambient air density [kg/m^3]
ρ_f	fuel density [kg/m^3]
C_a	area contraction coefficient [a.u.]
D	injector nozzle hole diameter [mm]
d_i	diameter of each individual droplet [μm]
P	pressure [Pa]
R	radial distance from the nozzle hole [mm]
T	temperature [K]
a	constant [a.u.]
Θ	spray cone angle [deg.]
Re	Reynold number [a.u.]
We	Weber number [a.u.]
ν	kinematic viscosity [m^2/s]
σ	surface tension [N/m]
V	mean injection flow velocity [m/s]

Abbreviations

ASA	advanced signal analyzer
C_2H_2	acetylene
CO	carbon monoxide
CVCC	constant volume combustion chamber
H_2	hydrogen
HC	hydrocarbons
N_2	nitrogen
NO_x	nitrogen oxide
O_2	oxygen
PDI	Phase Doppler Interferometry
PM	particulate matter
SMD	Sauter mean diameter
SO_x	sulphur oxides
WCO	waste cooking oil

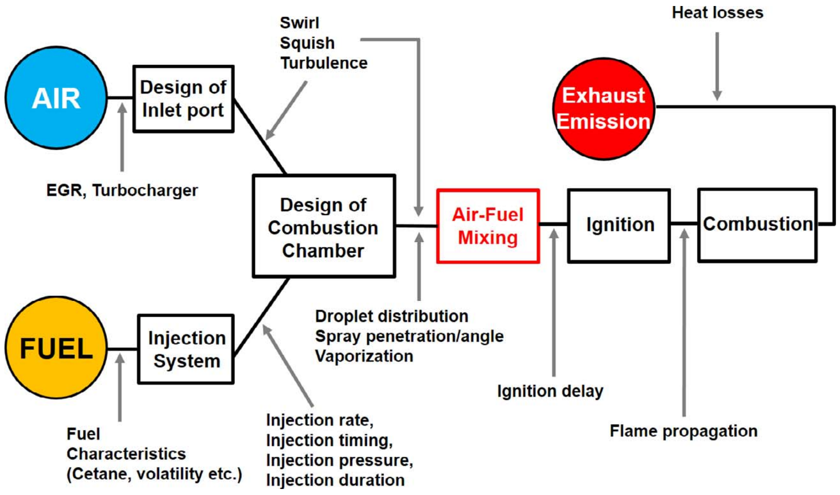

Fig. 1. Overall diesel spray and combustion process . reproduced from [6]

air motion induced by bulk flows such as squish flow, swirl, and tumble promote air-fuel mixing inside combustion chamber. Meanwhile, atomization and evaporation processes can be enhanced by higher injection pressure. The spray characteristics also can be affected by different fuel injection equipment (FIE) such as solenoid or piezo-electric injectors. The diesel combustion is occurred after mixture preparation period with a certain level of ignition delay and following heat release. It is appeared as a combination of partially pre-mixed combustion and partially diffusion combustion which can be determined by the quality of mixture formation during the ignition delay period [7]. Among the overall process, the primary factors which control the diesel combustion and emission characteristics are spray and air-fuel mixture formation [8,9]. Therefore, in-depth investigations of the atomization and evaporation characteristics should be carried out to comprehend the air-fuel mixing and subsequent combustion processes in diesel engines.

In the previous studies, the practice of using spray penetration results from non-evaporating conditions to represent evaporating sprays turned out to be only reasonable at very high density conditions [10]. Thus, many researchers are trying to perform spray experiment under simulated diesel engine ambient conditions in these days. Musculus et al., studied the effects of fuel parameters and flame lift-off length on soot formation in an optical diesel engine [11]. The experiments were conducted at two engine operating conditions using two commercial diesel fuels and a range of oxygenated paraffinic fuel blends. An OH chemiluminescence imaging was performed to measure flame lift-off length and a laser extinction diagnostic was employed to measure soot concentration. The experimental results showed that the fuel-bound oxygen in paraffinic fuels reduced soot emissions more efficiently than an equivalent quantity of entrained oxygen with conventional diesel fuel. The zero-soot formation threshold for oxygenated paraffinic fuels was predicted at overall oxygen-to-carbon (O/C) ratio of 0.55. In contrast, conventional diesel fuel showed much higher value, O/C ratio of 1.5. Lyle et al., studied diesel spray and combustion behavior using various high speed imaging technologies [12]. The experiments were performed under various ambient air conditions including non-evaporating/evaporating and non-reacting/reacting states. From the Mie-scattering and shadowgraph images, it was shown that the liquid tip penetration length reached a maximum axial penetration length, on the other hand, the vapor penetration length continued to penetrate across the chamber. The source of unburned hydrocarbons (UHC) was identified as remained fuel near injector nozzle due to the incomplete combustion based on simultaneous chemiluminescence and shadowgraph images.

Fuel spray and atomization characteristics depend on fuel properties such as density, viscosity, and surface tension [13,14]. In general, injectors designed by automotive manufacturers are intended for conventional diesel so the injector effectiveness differs according to the fuel properties. Hence, the effect of fuel properties on spray and combustion